Cosmological Gravitational Wave Background from Phase Transitions in Neutron Stars

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Abstract. It has recently been suggested that collapse of neutron stars induced by a phase transition to quark matter can be a considerable source of gravitational waves with kHz frequencies. We demonstrate that if about one percent of all neutron stars undergo this process, the resulting cosmological gravitational wave background would reach about 10^{-10} times the critical density. The background would peak at kHz frequencies and could have an observationally significant tail down to Hz frequencies. It would be comparable or higher than other astrophysical backgrounds, for example, from ordinary core collapse supernovae, from r-mode instabilities in rapidly rotating neutron stars, or from magnetars. The scenario is consistent with cosmological backgrounds in neutrinos and photons.

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1. Introduction

A phase transition from nuclear to quark matter within a neutron star (NS) with millisecond scale rotation period can induce a collapse that releases up to $\sim 10^{53}$ erg in energy, which potentially relates this process to violent phenomena such as core collapse supernovae [1] or $\gamma-$ray bursts (GRBs) [2, 3, 4]. Recent numerical simulations suggest that up to a few percent of this energy may be released as gravitational waves (GWs) [5].

If a significant fraction of NSs undergo such a phase transition induced collapse, the energy released will contribute to cosmological backgrounds in photons, neutrinos, and GWs. In the present paper we estimate these backgrounds and point out that the stochastic GW background may be comparable to GW backgrounds from various other astrophysical sources. We specifically compare the power and statistical properties of this potential background with the ones from standard core collapse supernovae [6], NS-NS coalescence [7, 8], r-mode instabilities in NSs with millisecond periods [9, 10], and from magnetars [11], as well as from various processes in the early universe. We also find a significant constraint on the fraction of the total energy released in such phase transitions in form of MeV $\gamma-$rays.

We use natural units with $\hbar = c = 1$ throughout.

2. The Source Mechanism

We first recall that the energy radiated in GWs per frequency interval for an individual event at distance D, $(dE_{\rm gw}/df)(f)$, is related to the Fourier transform $\tilde{h}(f) \equiv \int_{-\infty}^{+\infty} dt\, e^{-i2\pi ft} h(t)$ of the dimensionless strain amplitude $h(t)$ by

$$\frac{dE_{\rm gw}}{df}(f) = \frac{16\pi^2 D^2}{15 G_{\rm N}} \left| f\tilde{h}(f)\right|^2 , \qquad (1)$$

where $G_{\rm N}$ is Newton's constant.

We model the strain in the phase transition scenario as

$$h(t) \propto \exp\left(-\Gamma t\right) \sin f_0 t \quad \text{for} \quad t \geq 0 , \qquad (2)$$

which roughly reflects the form found in the simulations in Ref. [5]. This leads to a Fourier transform

$$|\tilde{h}(f)|^2 \propto \frac{f_0^2}{(f_0^2 - f^2 + \Gamma^2)^2 + 4\Gamma^2 f^2} , \qquad (3)$$

Note that the total energy emitted in GWs $E_{\rm gw}$ from Eq. (1) converges for this spectral form. We use $f_0 = 2\,$kHz, $\Gamma = 1/3\,$ms for the damping scale which is typical for the most rapidly rotating progenitors in Ref. [5], and normalize such that $E_{\rm gw} \simeq 2 \times 10^{51}$ erg, the more optimistic case from Ref. [5].

Most of the energy released in the phase transition is actually carried away in form of photons and neutrinos, whose total energy we will denote by $E_{\rm tot} \gtrsim (1-5) \times 10^{52}$ erg. This is roughly the energy required to power a $\gamma-$ray burst. The gravitational wave energy is typically $E_{\rm gw} \simeq 0.05 E_{\rm tot}$ [5].

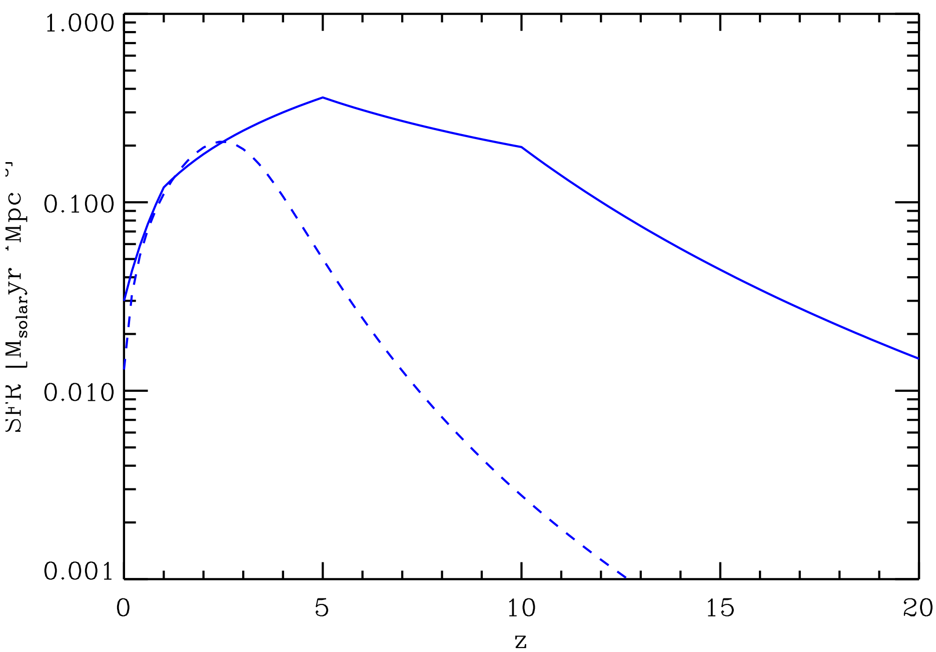

Figure 1. Models for the star formation rate as function of redshift. The solid line is from Ref. [15] which includes a putative PopIII component, whereas the dashed line respresents the Baldry & Glazebrook form [16] fitted in Ref. [13].

3. Cosmological Event Rates

The cosmic star-formation rate (SFR) and, as a consequence, the formation rate $R(z)$ of NSs is reasonably well known at redshifts $z \lesssim 5$ [12, 13]. Especially for $z \lesssim 1$ it is strongly constrained by the Super-Kamiokande limit on the electron antineutrino flux from cosmological core collapse supernovae [13, 14]. In contrast, the SFR is poorly known for $z \gtrsim 5$. We use the fits shown in Fig. 1.

We are interested in the number of events per unit mass. This number is given by an expression of the general form

$$\lambda \equiv \chi \frac{\int_{M_{\rm min}}^{M_{\rm max}} dm \xi(m)}{\int dm\, m\xi(m)}\,, \tag{4}$$

where we neglect any redshift dependence. Here, $\xi(m)$ is the mass function, usually taken to be of the Salpeter form $\xi(m) \propto m^{-2.35}$ between $0.1 M_\odot$ and $100 M_\odot$, $[M_{\rm min}, M_{\rm max}]$ is the progenitor mass range over which NSs form, and the integral in the denominator goes over all stellar masses. Further, χ is the fraction of NSs eventually undergoing the phase transition under consideration. The event rate $R(z)$ is then given by the product of the SFR and λ.

For NSs, $M_{\rm min} \simeq 10 M_\odot$, $M_{\rm max} \simeq 40 M_\odot$, so that $\lambda \simeq 5 \times 10^{-3}\, \chi\, M_\odot^{-1}$. Note that $\lambda \propto M_{\rm min}^{-1.35}$ and could be significantly larger if NSs are also formed from progenitors with masses $m < 10 M_\odot$. The above value for λ also roughly corresponds to today's rate of core collapse supernovae which is $\simeq 2 \times 10^{-4}\,{\rm Mpc}^{-3}\,{\rm yr}^{-1}$ which is to be expected

given that most of the NSs are born in type II supernova events. Most of the hot young NSs are born with 10-20 ms rotation periods due to processes such as magnetic braking. We assume that $\chi \simeq 1\%$ of the NSs undergo a phase transition. This is roughly the estimated fraction of NSs which are born with millisecond scale rotation periods [17, 18], required to trigger the phase transition. The same sub-population of NSs would be relevant for GW emission between $\sim 100\,\mathrm{Hz}$ and $\sim 2\,\mathrm{kHz}$ from r-mode instabilities in rapidly rotating NSs, in contrast to Ref. [9, 10] which assumed $\chi \sim 1$.

Another possible channel for phase transitions to occur in NSs is in low-mass X-ray binaries where the NS is spun up by accretion from the low mass companion [3, 19]. The formation efficiency of such systems is hard to estimate, but typical numbers are $\chi \sim 10^{-3} - 10^{-2}$ [20], similar to the estimated fraction of millisecond NSs born in core collapse supernovae.

Even larger values for λ could be motivated if these phase transitions are connected to short hard γ−ray bursts. A best estimate of $\sim 10^{-4}\,\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$ for the comoving rate of faint short hard γ−ray bursts at zero redshift has recently been given [21]. Comparing with Fig. 1, this corresponds to $\lambda \sim 5 \times 10^{-3}\,M_\odot^{-1}$, which would correspond to values for χ comparable to unity.

For the NS-NS coalescence and magnetar scenarios, λ is actually given by the same expression Eq. (4), with estimated fractions $\chi = 0.3\%$ [8] and $\chi = 8\%$ [11] of all NSs contributing, respectively.

We will neglect any time delay between star formation and NS formation because the lifetime $\sim 10^8\,\mathrm{yr}$ of $\gtrsim 10\,M_\odot$ NS progenitors is short compared to the Hubble time.

4. The Gravitational Wave Background

For simplicity, we assume that all NSs have identical emission characteristics.

The energy density in GWs at frequency f per logarithmic frequency interval in units of the cosmic critical density $\rho_\mathrm{c} = 3H_0^2/(8\pi G_\mathrm{N})$ can be written as [22]

$$\Omega_\mathrm{gw}(f) = \frac{1}{\rho_\mathrm{c}} \int_0^\infty dz\, \frac{R(z)}{1+z} \left|\frac{dt}{dz}\right| f_z \frac{dE_\mathrm{gw}}{df}(f_z)\,, \tag{5}$$

where $R(z)$ is the event rate per comoving volume, $f_z \equiv (1+z)f$. The cosmological model enters with $|dt/dz| = [(1+z)H(z)]^{-1}$ and, for a flat geometry,

$$H(z) = H_0 \left[\Omega_\mathrm{M}(1+z)^3 + \Omega_\Lambda\right]^{1/2}\,. \tag{6}$$

We will use the parameters $\Omega_\mathrm{M} = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = h_0\,100$ km s^{-1} Mpc^{-1} with $h_0 = 0.72$.

For a stochastic GW background the dimensionless strain power $\left|f\tilde{h}(f)\right|^2$ is related to the dimensionless GW energy density in Eq. (5) by [22]

$$h_0^2\,\Omega_\mathrm{gw}(f) = \frac{2\pi^2 h_0^2}{3H_0^2} f^2 \left|f\tilde{h}(f)\right|^2 = 6.25 \times 10^{35} \left(\frac{f}{\mathrm{Hz}}\right)^2 \left|f\tilde{h}(f)\right|^2\,. \tag{7}$$

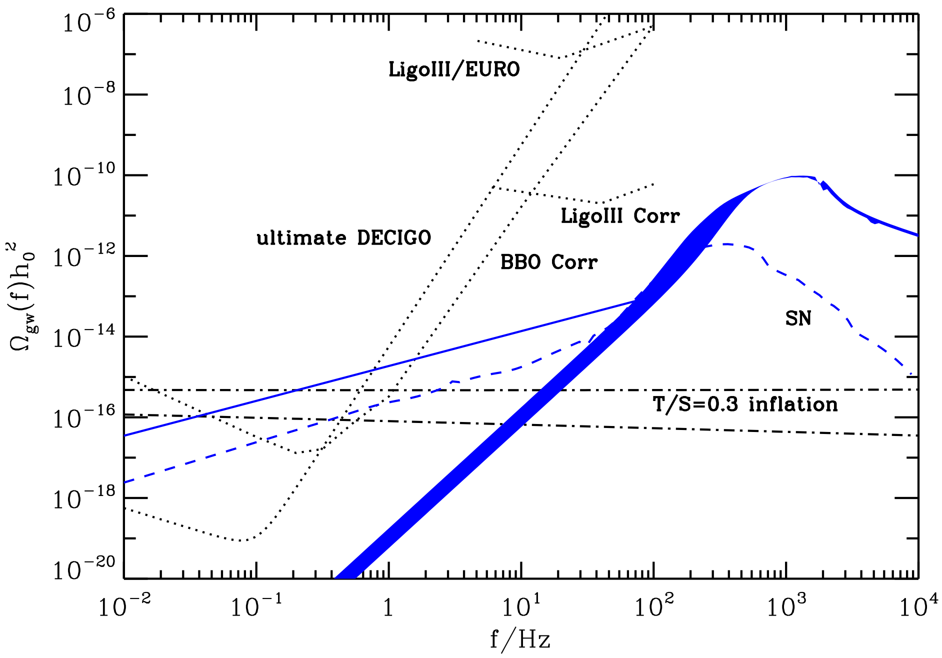

Figure 2. Spectrum of GW background from Eq. (5) assuming about $\chi = 1\%$ of all NSs undergo a phase transition, releasing $E_{\rm gw} \sim 2 \times 10^{51}$ erg in GWs. The band represents the uncertainty related to the different SFRs shown in Fig. 1. The solid line is the maximal low-frequency tail due to anisotropic neutrino emission. For comparison, the dashed line is the maximal background from conventional type II supernovae discussed in Ref. [6]. Further, the horizontal dash-dotted lines represent a maximum version of the GW stochastic spectrum produced during slow-roll inflation assuming $T/S = 0.3$ for the ratio of the tensorial and scalar contributions to the cosmic microwave background radiation anisotropy and $\pm 10^{-3}$ for the running of the tensorial power-law index [23]. The dotted lines show approximate sensitivities of the ground based interferometer LigoIII/EURO and LigoIII in correlation mode [24], and of possible second generation space-based interferometers such as the Big Bang Observatory (BBO) [25] and the ultimate DECIGO [26], as indicated.

Fig. 2 shows the resulting GW background for the NS phase transition scenario, the band representing uncertainties due to the different SFRs from Fig. 1, but not due to other quantities such as $E_{\rm gw}$ and χ which were fixed to fiducial values, as indicated. Note that GW densities are proportional to λ from Eq. (4), and thus also to the fraction χ of NSs subject to the phase transition. They are also proportional to the average total GW energy output $E_{\rm gw}$. As a result, the largest uncertainties come from the parameters χ and $E_{\rm gw}$, whereas uncertainties due to the SFR are moderate because the background is dominated by redshifts $z \lesssim 3$ where the SFR is reasonably well known, see Fig. 1.

The stochastic GW background from cosmological supernovae was studied recently in Ref. [6], and its optimistic estimate is reproduced in Fig. 2. While the event rate $R(z)$ used there is higher than in the present scenario (since supposedly only a percent fraction of core collapse supernovae likely give rise to NSs rotating rapidly enough to undergo phase transitions), the individual source signal is very different: In the phase

transition scenario, the signal from one event at kHz frequencies is much higher than the one due to convection in the simulations in Ref. [27] and, as a consequence, the total energy emitted in GWs is much larger, $\sim 10^{-3}\,M_\odot$ versus $\sim 10^{-8}\,M_\odot$. As a result, the background from phase transitions can be comparable or higher (above ~100 Hz) to the background from conventional type II supernovae.

There could also be an enhanced low frequency tail if the strain $h(t)$ converges to a non-vanishing constant for $t \to \infty$ due to anisotropic neutrino emission [28, 29]. For $f \ll$kHz, $dE_{\rm gw}/df \simeq 15 G_{\rm N}\,(E_\nu q)^2$ [6], where $E_\nu \leq E_{\rm tot}$ is the total energy emitted in neutrinos, and $|q| \lesssim 1$ is the average dimensionless quadrupole. Whereas E_ν is about an order of magnitude smaller than $E_\nu \sim 3 \times 10^{53}\,$erg in standard type II supernovae, the anisotropy could be much larger than the order percent anisotropy expected in hot NSs without phase transition [27]. This is because the NS would oscillate strongly and be highly deformed after the phase transition. In one of the simulations in Ref. [5], for example, the ratio of the polar to equatorial radius is $\simeq 0.7$. As in core collapse supernovae, the neutrinos would likely be partially trapped and emitted from a neutrinosphere because the release of $\sim 5 \times 10^{52}\,$erg in internal energy would heat up the NS to $\sim 10 - 20\,$MeV.

We can parametrize the low-frequency tail as

$$\Omega_{\rm gw}(f) \sim 3.5 \times 10^{-15}\left(\frac{E_\nu q}{5\times 10^{52}\,{\rm erg}}\right)^2 \left(\frac{\lambda}{5\times 10^{-5}\,M_\odot^{-1}}\right)\left(\frac{f}{\rm Hz}\right)\,. \tag{8}$$

The maximum of this tail, corresponding to the fiducial values in Eq. (8) is shown in Fig. 2 and reflects the uncertainty in the low-frequency signal: In the absence of a "GW memory effect", $\tilde{h}(f) \to$const, see Eq. (3) and thus $\Omega_{\rm gw}(f) \propto f^3$ for $f \to 0$, see Eqs. (1) and (5). In contrast, in the presence of burst with memory $f\tilde{h}(f) \to$const and $\Omega_{\rm gw}(f) \propto f$ for $f \to 0$.

Fig. 3 shows various other astrophysical backgrounds for comparison: The solid line shows a possible popcorn like signal from NS-NS coalescence [8]. We note that other work used a lower maximal frequency which would cut off the signal above $\sim 200\,$Hz [7]. The dotted line shows a stochastic background from r-mode instabilities emitting GWs between $\sim 100\,$Hz and $\sim 1.4\,$kHz. It has been corrected by the small fraction $\chi \sim 1\%$ of all NSs nowadays believed to be born with sufficiently small, millisecond scale rotation periods, in contrast to the original Refs. [9, 10] which assumed that a substantial fraction of all NSs are born with rotation periods close to maximal. Finally, the dashed line represents the magnetar scenario [11]. The NS phase transition scenario could thus produce a background which is comparable to or larger than these backgrounds both at kHz frequencies and below $\sim 10\,$Hz.

Finally, the background from NS phase transitions shown in Fig. 2 would potentially mask several possible GW relic backgrounds from the early universe, at least at frequencies between $\simeq 0.1\,$Hz and $\sim 1\,$Hz, where it becomes close to gaussian and thus indistinguishable to other gaussian backgrounds, see next section. Such early universe backgrounds include the one from standard inflation whose maximum is shown

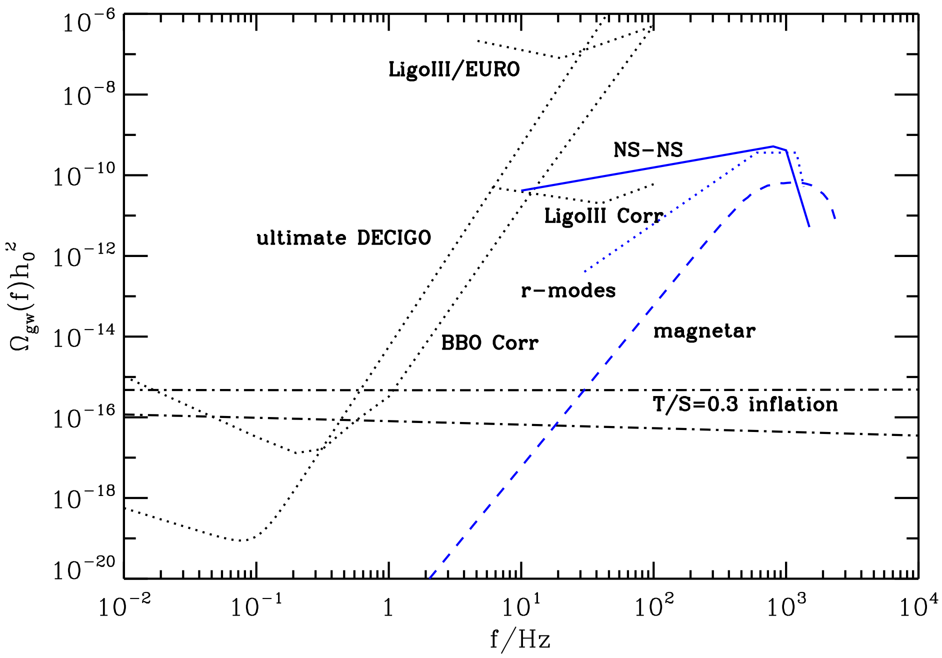

Figure 3. GW backgrounds from various other astrophysical mechanisms for comparison to Fig. 1. The solid line represents that part of the NS-NS coalescence signal from Ref. [8] which has a "popcorn"-character, similar to the phase transition scenario considered here, see below. The dotted line corresponds to GWs from r-mode instabilities emitted by the fastest rotating NSs [9, 10], assumed to constitute a fraction $\sim 1\%$ of all NSs. The dashed line shows the magnetar scenario [11].

in Fig. 2, but also more speculative ones such as from quintessential inflation which predicts $\Omega_{\rm gw}h_0^2 \sim 6\times 10^{-16}(f/{\rm Hz})$ above $\sim 10^{-3}\,$Hz [30].

5. Statistical Properties of Gravitational Wave Background and Detectability

The event rate as seen from Earth is

$$\int_0^\infty dz\,\frac{R(z)}{1+z}\frac{dV}{dz} = \int_0^\infty dz\,R(z)\frac{4\pi r^2(z)}{(1+z)H(z)}\,, \tag{9}$$

where dV/dz is the fractional volume element, the cosmic expansion rate at redshift z is given by Eq. (6), and $r(z)$ is the comoving coordinate, $dr=(1+z)dt$.

The duty cycle can be estimated by multiplying the integrand of Eq. (9) with $(1+z)t_{\rm coh}[(1+z)f]$, where $t_{\rm coh}(f)$ is the timescale over which the frequency f is emitted coherently. A probably more realistic estimate is obtained by weighting the resulting integral over redshift with the redshift dependent contribution to the GW signal given by the integrand in Eq. (5).

Fig. 4 shows the duty cycle obtained by these two estimates for the NS phase transition scenario for which $t_{\rm coh}(f)\simeq \max(1/\Gamma, 1/f)$. If it is smaller than one, the duty cycle roughly corresponds to the variable ξ in Ref. [31]. The background is thus

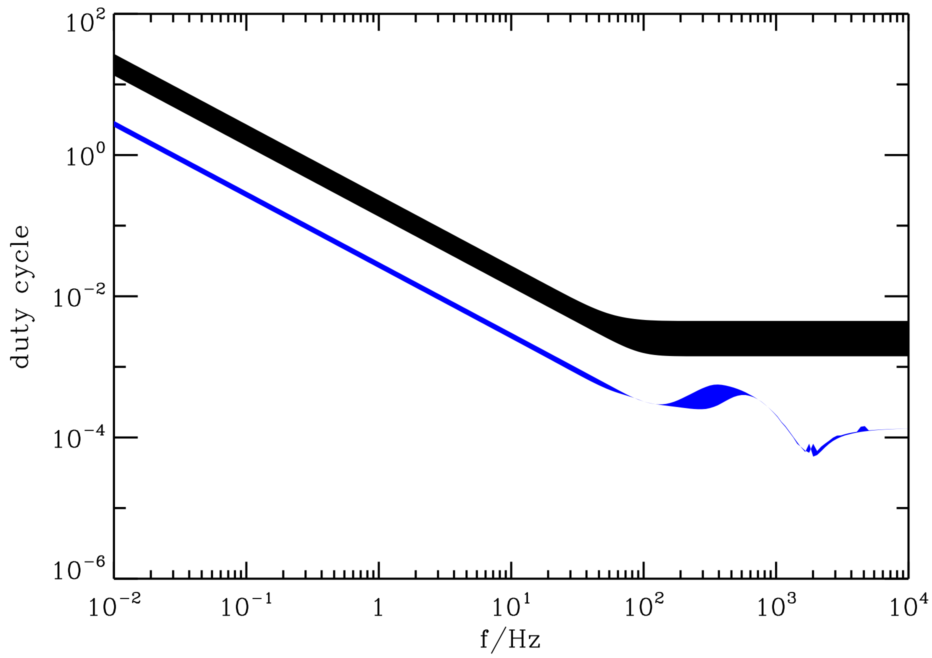

Figure 4. The duty cycle as function of frequency for the NS phase transition scenario. The blue (lower) band includes weighting with the GW signal, whereas the dark (upper) band does not. Again, the bands represent the uncertainty related to the different SFRs shown in Fig. 1.

of "popcorn" character. Note that the duty cycle is proportional to λ. The minimal detectable GW energy density $\Omega_{\rm gw}$ for a popcorn signal is comparable or, for duty factors smaller than a few percent, smaller by factors of a few compared to the minimal detectable background for gaussian noise [31]. Thus for $\lambda \sim 5 \times 10^{-3}\, M_\odot^{-1}$, the signal would have a duty factor of a few percent and may thus be marginally detectable by third generation interferometers in correlation mode, see Fig. 2. This would require, however, that a fraction of order one of NSs would have to contribute, which is unlikely. Also note that microwave cavity detectors could reach sensitivities of order $\Omega_{\rm gw} \sim 10^{-9}$ at a few hundred Hz [32, 33].

The most advanced interferometers planned for the future such as GEO-HF [34] can reach sensitivities around $f^{1/2}\tilde{h}(f) \sim 5 \times 10^{-24}\,{\rm Hz}^{-1/2}$ in the $1 - 10\,$kHz regime. One can easily deduce from Eqs. (1) and (3) that for a source at distance D (small compared to the Hubble radius), the maximum of $f^{1/2}\tilde{h}(f)$ occurs at $f \simeq 2\,$kHz with $f^{1/2}\tilde{h}(f) \simeq 3\times10^{-23}\,(D/10\,{\rm Mpc})^{-1}\,{\rm Hz}^{-1/2}$ for the phase transition scenario. Such events would thus be detectable out to $\sim 10\,$Mpc, with a rate $\simeq 0.2\,(\chi/0.01)(D/10{\rm Mpc})^3\,{\rm yr}^{-1}$.

At $f \sim$kHz the signal from core collapse supernovae has a duty cycle slightly higher than the one of the phase transition signal if $\chi \sim 1\%$ of the NSs contribute to the phase transition signal. This is because the supernova rate is then roughly a factor 100 higher, whereas the coherence time $t_{\rm coh}(f) \simeq 1/f$ for the incoherent process of convection is slightly shorter than the one of the oscillations right after the phase transition, for which

$t_{\rm coh}(f) \simeq 3\,{\rm ms}$.

For both the r-mode instability [9, 10] and magnetar [11] scenarios, $t_{\rm coh}(f) \gg 1/f$, and the signal is Gaussian at all observable frequencies. The NS-NS coalescence signal consists of a gaussian, a popcorn, and a shot noise component [8]. A fraction of $\chi \sim 0.003$ of all NSs are in suitable binaries to contribute to the coalescence signal. As a consequence, the background has statistical properties similar to the one for NS phase transitions. The total power from NS-NS coalescence shown in Fig. 3 can be comparable or somewhat higher than for the NS phase transition scenario because the gravitational energy released is higher, $E_{\rm gw} \sim 5 \times 10^{52}\,{\rm erg}$ [8].

6. Electromagnetic and Neutrino Emissions

The energy going into GWs during the phase transitions considered in Ref. [5] represents only a fraction of a few percent of the total energy released $E_{\rm tot}$. Fig. 2 shows that an energy $E_{\rm gw} \simeq 2 \times 10^{51}\,{\rm erg}$ released per event in GWs and a number of events per unit mass $\lambda \simeq 5 \times 10^{-5} M_\odot^{-1}$ corresponds to $\Omega_{\rm gw} \sim 10^{-10}$, quite independent of the poorly known high redshift evolution of the SFR. By simple scaling, this implies an energy density

$$\Omega_{\nu+\gamma} h_0^2 \simeq 3 \times 10^{-9} \left(\frac{E_{\rm tot}}{5 \times 10^{52}\,{\rm erg}}\right) \left(\frac{\lambda}{5 \times 10^{-5} M_\odot^{-1}}\right) \tag{10}$$

is released in form of photons and/or neutrinos. Photons and neutrinos are expected to be emitted on timescales $\gtrsim 10\,{\rm s} \gg 1/\Gamma$ than GWs, a factor $\gtrsim 3 \times 10^3$ larger than GWs which are emitted on a timescale $\simeq 1/\Gamma \simeq 3\,{\rm ms}$. Fig. 4 then implies that these backgrounds are quasi-continuous for $\lambda \gtrsim 5 \times 10^{-5}\, M_\odot^{-1}$, provided the emissions are not strongly beamed.

This emission can certainly not be predominantly in form of MeV $\gamma-$rays because the cosmological diffuse background of photons above an MeV has an energy density $\Omega_{\rm MeV} h_0^2 \simeq 4 \times 10^{-10}$. Put another way, the fraction $f_{\rm MeV}$ that can be released in these events is constrained by

$$f_{\rm MeV} \lesssim 0.1 \left(\frac{E_{\rm tot}}{5 \times 10^{52}\,{\rm erg}}\right)^{-1} \left(\frac{\lambda}{5 \times 10^{-5} M_\odot^{-1}}\right)^{-1} . \tag{11}$$

Since the energy density in lower energy backgrounds are larger, no significant constraint on the fraction going into photons of energy below $\sim 100\,{\rm keV}$ result.

Obviously, if only a very small fraction of the SFR contributes to these events, i.e. if λ is small, and/or the total energy released $E_{\rm tot}$ is small, this constraint becomes weak or disappears. However, the fiducial values for λ and $E_{\rm tot}$ used here are not unrealistic, and imply significant constraints on emission into MeV $\gamma-$rays.

If phase transitions are to be associated with GRBs, a fraction

$$f_{\rm MeV} \sim 10^{-3} \left(\frac{E_{\rm tot}}{5 \times 10^{52}\,{\rm erg}}\right)^{-1} \left(\frac{\lambda}{5 \times 10^{-5} M_\odot^{-1}}\right)^{-1} \tag{12}$$

released as $\sim$ MeV $\gamma-$rays would in fact be sufficient because GRB emissions correspond to a (non-continuous) photon background with energy density $\Omega_{\rm GRB} \sim 2 \times 10^{-12}$. Since $\sim 10^3$ GRBs are visible per year, this would imply a beaming factor

$$\sim 3 \times 10^3 \left(\frac{\lambda}{5 \times 10^{-5} M_\odot^{-1}} \right) . \qquad (13)$$

The corresponding Lorentz factor would be roughly the square root of this.

7. Conclusions

We have estimated the cosmological background of gravitational waves for the scenario where a fraction $\chi \sim 1\%$ of all neutron stars are born as millisecond pulsars and undergo a phase transition to a quark star, releasing $\sim 10^{51}$ erg in gravitational waves, as suggested by recent simulations. In terms of the corresponding event rate per unit stellar mass, λ, this background would have a duty factor of $\sim 5 \times 10^{-4} \left[\lambda/(5 \times 10^{-5}\, M_\odot^{-1})\right]$ above $\sim 50\,$Hz and $\sim 0.03 \left[\lambda/(5 \times 10^{-5}\, M_\odot^{-1})\right] (f/{\rm Hz})^{-1}$ below $\sim 50\,$Hz. However, most of the energy flux is at kHz frequencies, a factor 10-100 above the maximum sensitivity of ground based interferometers. Using statistics specialized to detecting popcorn type noise with collocated aligned detectors at the technological limit, the background may be marginally detectable around 100 Hz for $\lambda \sim 5 \times 10^{-3}\, M_\odot^{-1}$ which is only possible if the majority of all neutron stars would be born with millisecond periods and undergo a phase transition. In this unrealistic case the background would have duty factors of a few percent.

The total energy in gravitational waves can be, however, quite substantial even for moderate fractions χ of neutron stars contributing. In units of the critical density one obtains $\Omega_{\rm gw} h_0^2 \sim 10^{-10} \left[E_{\rm gw}/(2 \times 10^{51}\,{\rm erg})\right] (\chi/0.01)$. In addition, since neutrinos tend to be emitted very anisotropically in the form of jets, there could be a low-frequency tail of order $\Omega_{\rm gw}(f) \lesssim 10^{-15} \left[\lambda/(5 \times 10^{-5}\, M_\odot^{-1})\right] (f/{\rm Hz})$, likely larger than for ordinary type II supernovae. A low-frequency tail of that size would mask the maximal gravitational background in ordinary inflation models between $\sim 0.1\,$Hz and $\sim 1\,$Hz where it would also be gaussian. At these frequencies this tail could be detectable by future space based interferometer projects such as BBO or DECIGO.

The gravitational wave background from phase transitions in rapidly rotating newly born neutron stars can thus be comparable or higher than other astrophysical backgrounds. Detection of such a signal could provide insight into the nature of compact objects.

If most of the energy released in the phase transition is in form of neutrinos, the resulting diffuse MeV neutrino flux would constitute $\sim 10^{-3}(\chi/0.01)$ of the flux due to standard type II core collapse supernovae, and would thus be consistent with existing upper limits [14]. The fraction of the energy released in form of MeV $\gamma-$rays is constrained by observed diffuse backgrounds to be less than $\sim 10\%(\chi/0.01)^{-1}$. A fraction $\sim 10^{-3}(\chi/0.01)^{-1}$ released into the band of $100\,{\rm keV} - 1\,{\rm MeV}$ $\gamma-$rays would suffice to account for $\gamma-$ray bursts.

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